

Decadal land-use/land-cover and land surface temperature change in Dubai and implications on the urban heat island effect: A preliminary assessment

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Abstract: The emirate of Dubai is the most populous and most developed of the seven emirates that comprise the United Arab Emirates (UAE). By the end of the 20th century, the emirate had shifted its economy from being primarily petroleum-based to a focus on tourism and financial services. The emirate's capital, also named Dubai, has been growing at a rapid pace; the population in 1999 was 862,000 inhabitants, and increased in ten years to 1.8 million. In this letter, I evaluate the extent of land cover and land surface temperature change between 1999 and 2009. Landsat ETM+ satellite images from the month of September 1999 and 2009 were used in this study. Both images were classified using spectral information divergence to measure the discrepancy of probabilistic behaviors between spectral signatures of different surfaces in the study area. Changes in land cover between 1999 and 2009 were quantified using post-classification analysis in a geographic information system. The results have shown a 76.11% change in land cover and a 1.75°C average increase in land surface temperature over the 10-year study period. The composition of land cover features significantly influence the magnitude of land surface temperature and the percent cover of stabilized land and impervious surfaces have had the most substantial affect. In contrast, the percentage of vegetation cover is the most essential driver that alleviates land surface and ambient temperature. Keeping the cooling effects of urban greenery in perspective, I suggest that their proper management can directly mitigate the urban heat island effect in Dubai.

Keywords: Dubai; Land-cover; Land-use; Land surface temperature; Landsat; ETM+; Persian Gulf; UAE; Urban heat island.

1. Introduction

The United Arab Emirates (UAE) is a federation of seven emirates located on the southeastern shore of the Persian Gulf (Figure 1). The emirate of Dubai is the most populous and most developed of the seven emirates that comprise the country. By the end of the 20th century, the emirate shifted its economy from being primarily petroleum-based to a focus on tourism and financial services. The emirate's capital, also named Dubai, has been growing at a rapid pace; the population in 1999 was 862,000 inhabitants, which more than doubled in ten years to 1.8 million by 2009 [1]. This growth has been accompanied by ambitious land reclamation projects that included artificial islands such as the

“Palm Jebel Ali”, “Palm Jumeirah”, “Palm Deira” and “The World”. These offshore features, as well as the altered landscape of the area, are easily discernable using medium resolution satellite imagery.

Earth observation data has been used extensively in recent years to monitor changes at a global [2], regional [3] and local levels [4]. In the UAE, remote sensing studies have been primarily focused on land management and vegetation mapping [5, 6, 7], coastal sensitivity mapping [8, 9], and urban land use and land cover [10, 11].

The objectives of this study are: (1) to quantify changes in land cover and assess the effects of urbanization in the Dubai metropolitan area; (2) to derive land surface temperature change in the metropolitan area and analyze its spatial variations; and (3) to investigate the relationship between land surface temperature and land cover.

2. Methods

2.1. Study Area

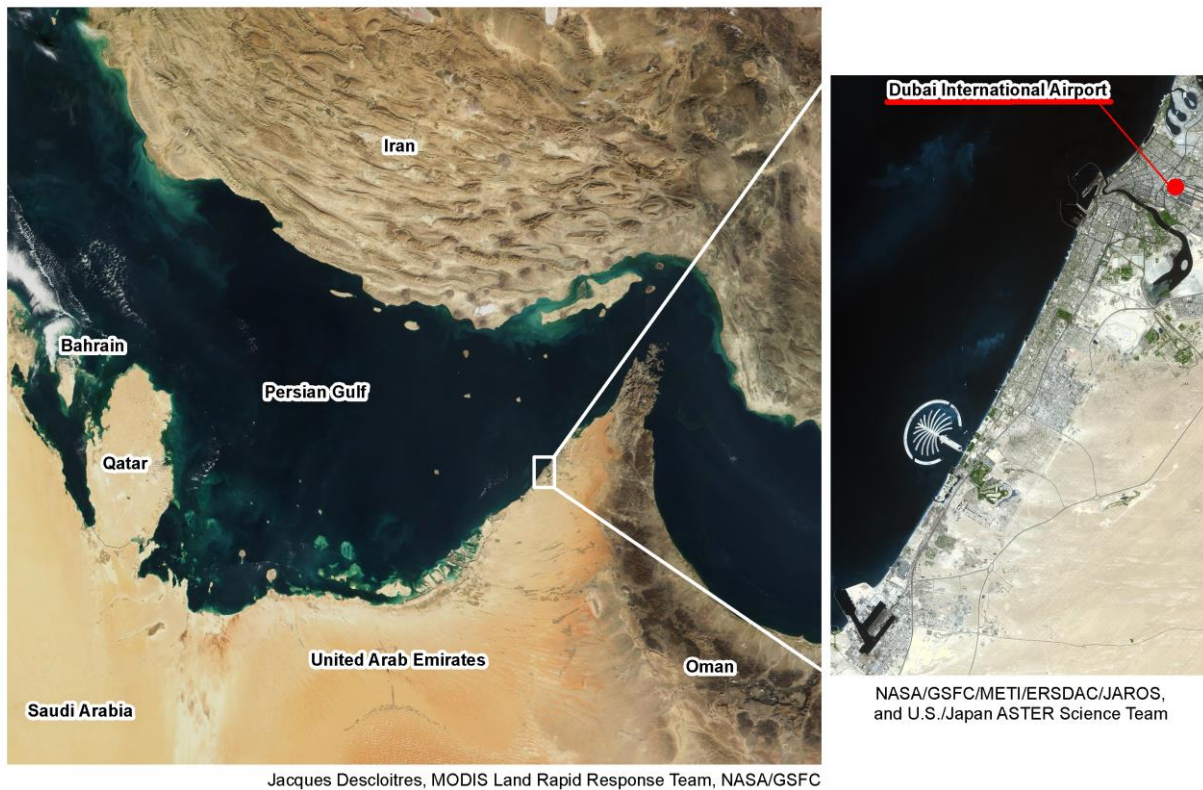
The study area is the Dubai Metropolitan Area (Figure 1), which includes the sections of Jumeirah, Bur Dubai, Deira and Jebel Ali. The southern border of the study area is the Dubai Outer Road. The westernmost extent is the Palm Jebel Ali and the easternmost extent is the Palm Deira (currently under construction).

2.2. Data

The Enhanced Thematic Mapper Plus (ETM+) sensor on board the Landsat 7 satellite was used to provide the required imagery. Scenes from the month of September for the years 1999 and 2009 were downloaded from the USGS Global Visualization Viewer (GLOVIS). The imagery is standard level one terrain corrected (L1T) and has systematic radiometric and geometric correction through the incorporation of ground control points and a digital elevation model. I chose ETM+ because it offers high temporal and medium spatial resolutions for no cost. Landsat imagery has been extensively used in recent years and is proven adequate for this type of study [12, 13]. However, the ETM+ Scan Line Corrector (SLC) has been inoperational since May 2003; this malfunction has caused the imagery to possess a number of data gaps in the form of diagonal striations (Figure 5A, supplemental material). Most of the study area lies in the unaffected zone, and the part that is affected is comprised of relatively narrow bands that were 150m wide at their thickest and 60m wide at their narrowest. Therefore, prior to classification, the scene had to be preprocessed in order to fill the areas that were devoid of data. I used cubic spline interpolation in MATLAB to fill the regions that had no data. This method was preferred over linear interpolation because the interpolation error was low even when using low degree polynomials for the spline. MATLAB performs a one-dimensional interpolation by fitting the supplied data with polynomial functions between data points and evaluating the appropriate function at the desired interpolation points. This technique proved successful, as the resultant scene was free of data gaps (Figure 5B, supplemental material). I then corrected the images for atmospheric effects using the QUick Atmospheric Correction method (QUAC), which determines parameters directly from information present in the scene through the utilization of observed pixel spectra. QUAC is an in-scene approach to atmospheric correction and allows the collection of fairly accurate

reflectance spectra even when the sensor does not possess appropriate radiometric calibration or when certain parameters such as the solar intensity are unknown [14].

Figure 1. Overview of the United Arab Emirates and the city of Dubai. The location of the Dubai International Airport weather station is highlighted and will be discussed later in the text.



2.3. Land Cover Classification

Images were classified in ENVI using spectral information divergence (SID) [15], a stochastic spectral similarity method that employs a quantification of divergence that correspond pixels to particular reference spectra. The pixels are likely to be analogous if the divergence value is low. A threshold level was specified and pixels having measurements greater than that level are excluded from the classification. Representative training data were collected for each class using regions of interest (ROIs) and endmember reference spectra were calculated using the average spectra values in each class. SID presents a different perspective of the similarity between two spectral signatures through the use of the concept of divergence [16] to calculate the inconsistency of probabilistic behaviors of the spectral information provided by each signature. I used the enhanced vegetation index, (EVI) [17] to discriminate green areas from the rest of the urban landscape. EVI augments the vegetation signal, reduces soil background noise and removes any remaining effects from the atmosphere [17].

Table 1. Description of land cover classes selected for the study.

Class	Description
Bare Ground	Exposed soil, rock or consolidated hard surfaces resulting from sand stabilization activities. These surfaces are not covered by vegetation or sand.
High Intensity Urban	Highly developed areas where people reside or work in high numbers e.g. apartment complexes and commercial/industrial buildings. Impervious surfaces account for 80 to 100 percent of the total cover.
Low Intensity Urban	Areas with a mixture of constructed space and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include family villas and neighborhoods with ample greenery such as parks and roadside vegetation.
Loose or Shifting Sand	Areas of natural desert, covered by sand particles that may be moved by regularly occurring winds and form clear directional patterns.
Vegetation	Green urban areas e.g. parks and gardens. EVI value >0.0

2.4. Land Surface Temperature

The urban climate of Dubai is affected by changes in land use, vegetation cover, and the expansion of built-up areas, hence, land surface temperature (LST) was included in the analysis as an indicator of urban expansion, and to detect urban heat island (UHI) effects. Radiation released by terrestrial surfaces is recorded by LST; hence, it could be influenced by the spatial arrangement of an urban landscape.

In order to measure change in LST from 1999 and 2009, radiant temperatures were derived from ETM+ thermal infrared data (band 6) following steps outlined in the Landsat 7 Science Data Users Handbook [18], emissivity was calculated using methodology described in Sobrino et. al. [19], and surface temperature was derived using the methodology in Weng et. al. [13]. Mean LST estimate per land cover class was calculated using polygon summary statistics in a geographic information system (GIS) by superimposing LST data (in raster format) with the corresponding land cover data (in vector format).

Since there were no offshore developments in 1999, I created a land/water mask using the 2009 image to extract areas of offshore development and then superimposed that mask on the earlier image to quantify areas of water in 1999 that were converted to other land cover classes in 2009. I then used an error matrix to assess the accuracy of the land cover maps by comparing the classification results with reference data. The 1999 land cover map was validated using 500 random reference samples (100 per land cover class) collected in October 1999, and reference data for the 2009 land cover map were

collected using 500 random samples (100 per land cover class) collected from high resolution Google Earth imagery from September 2009 (Figure 4, supplemental material). Overall accuracy and Kappa coefficient [20] were used to measure the performance of the classification. Kappa is a measure of agreement and accuracy with values greater than 0.80 represent strong agreement between the classified image and the reference data [21].

3. Results and Discussion

The overall accuracy of the land cover maps for 1999 and 2009 were 91.86% and 84.04%, respectively (Table 2). Kappa values for 1999 and 2009 were 0.88 and 0.81, respectively. It is evident from these data that the reasonably high accuracy of the classification is appropriate for the stated purposes of this study. Table 3 displays the land cover change matrix from 1999 to 2009, and it is clear that there has been a substantial change (76.11%) in the land cover of the total area.

The High and Low Intensity Urban areas exhibited the largest percent increase (354.47% and 120.35%, respectively) followed by Vegetation (94.36%). This urban sprawl is directional towards the east and southwest. The eastward trend could reflect the creation of suburban commuter districts caused by the two-fold increase in population during the 10-year period of the study. The southwest trend could be caused by commercial expansion of the Jebel Ali Industrial Zone.

Table 2. User's and Producer's accuracies and Kappa coefficients for the classification results.

Classes	1999 Classification		2009 Classification	
	Accuracy (%)		Accuracy (%)	
	Prod. Acc.	User Acc.	Prod. Acc.	User Acc.
High Intensity Urban	82.98	86.02	84.65	68.52
Low Intensity Urban	89.81	72.66	87.33	94.03
Vegetation	99.27	87.82	97.12	99.80
Bare Ground	69.24	98.99	65.47	84.48
Loose or Shifting Sand	99.76	84.21	92.40	80.00
Overall Accuracy (%)	91.86		84.04	
Kappa Coefficient	0.88		0.81	

Table 3. Results of the change detection analysis (km²). The water mask provided useful information about the area of water that was displaced by different land cover classes.

	Final Land Cover (2009)						1999 Total (km ²)
	High Intensity Urban	Low Intensity Urban	Vegetation	Loose or Shifting Sand	Bare Ground	Water	
High Intensity Urban	22.03	4.63	0.31	0.00	0.00	0.00	26.97
Low Intensity Urban	54.59	167.33	7.98	0.00	0.03	0.00	229.93
Vegetation	2.23	2.01	10.47	0.00	0.01	0.00	14.72
Loose or Shifting Sand	10.82	164.41	6.32	485.98	454.56	0.00	1122.09
Bare Ground	20.53	131.62	3.49	1.51	224.76	0.00	381.91
Water	12.37	36.65	0.04	0.45	17.72	0.00	67.23
2009 Total (km ²)	122.57	506.65	28.61	487.94	697.08	0.00	1842.85
Change (km ²)	95.60	276.72	13.89	-634.15	315.17	-67.23	1402.76
Change (%)	354.47	120.35	94.36	-56.52	82.52	-100.00	

Table 4. Mean land surface temperature in degrees Celsius by land cover type.

Class	1999		2009		ΔT
	Mean	Standard Deviation	Mean	Standard Deviation	
Bare Ground	51.35	6.13	55.26	7.47	+3.91
High Intensity Urban	48.84	2.40	51.18	3.36	+2.34
Low Intensity Urban	45.10	3.61	46.89	3.74	+1.79
Loose or Shifting Sand	47.83	0.52	48.09	0.58	+0.26
Vegetation	33.54	1.04	33.98	1.74	+0.44

Table 4 shows the mean values of LST by land cover type in 1999 and 2009. The high temperature exhibited by the Bare Ground land cover class in 2009 (55.26°C) could be attributed to the application of mechanical or chemical stabilization methods such as leveling with heavy machinery and the use of lime mixtures on areas of Loose and Shifting Sand that were covered in preparation for development. This lowers the albedo and increases absorption of incident solar energy.

It is clear that Low Intensity Urban areas are cooler than High Intensity ones due to the greater prevalence of urban vegetation. This cooling effect is related to the 94.36% increase in urban vegetation between 1999 and 2009. In contrast, there has been a 2.06°C increase in mean urban LST, which is explained by the increase in non-porous, and non-evapotranspirative materials that constitute the High and Low Intensity Urban landscapes [22]. Note that this increase in urban LST is higher than mean increase in all land cover types (1.75°C) indicating that the urban landscape drives climatic conditions within its vicinity.

Figure 2. Land cover and land surface temperature maps of the Dubai Metropolitan Area for 1999 and 2009.

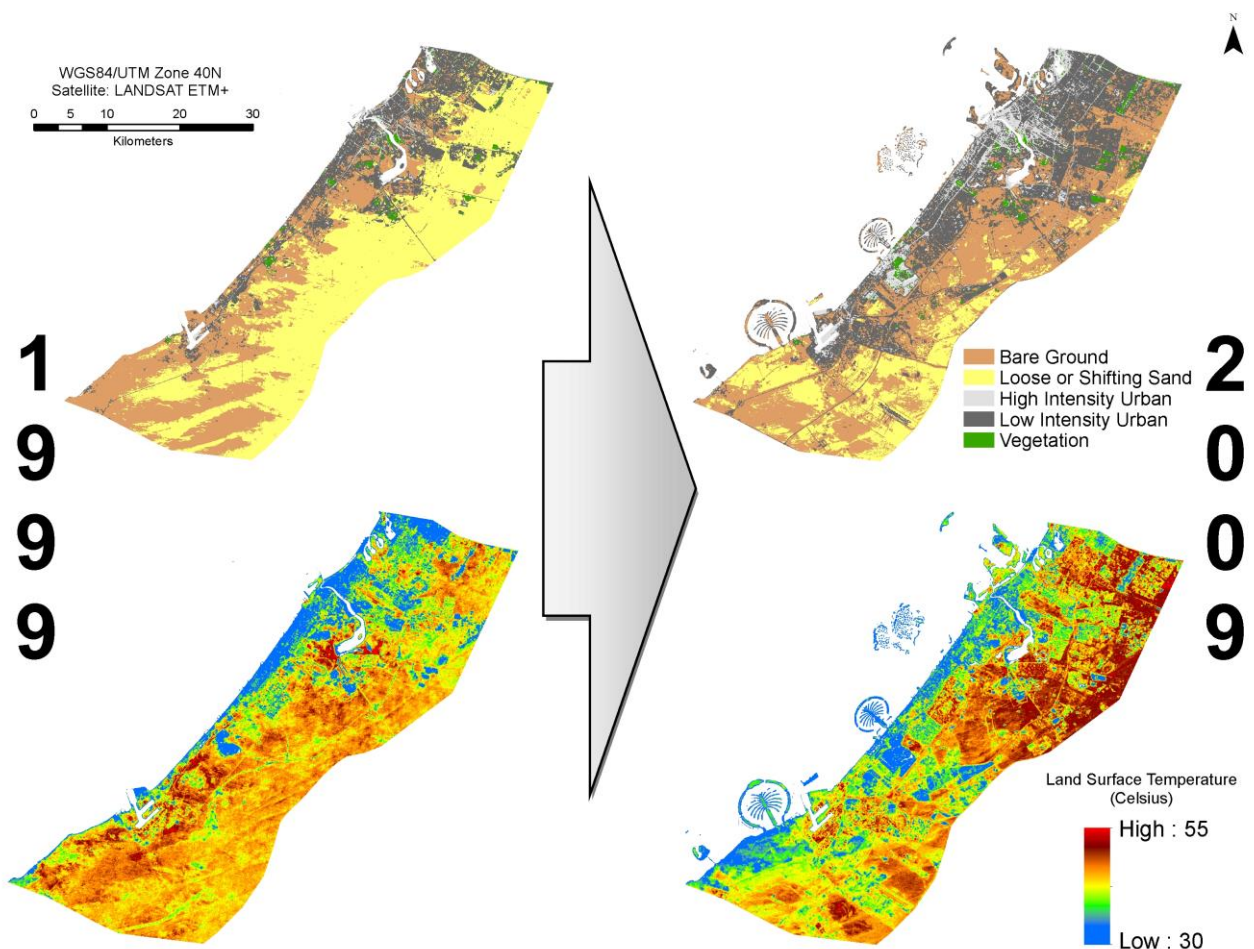
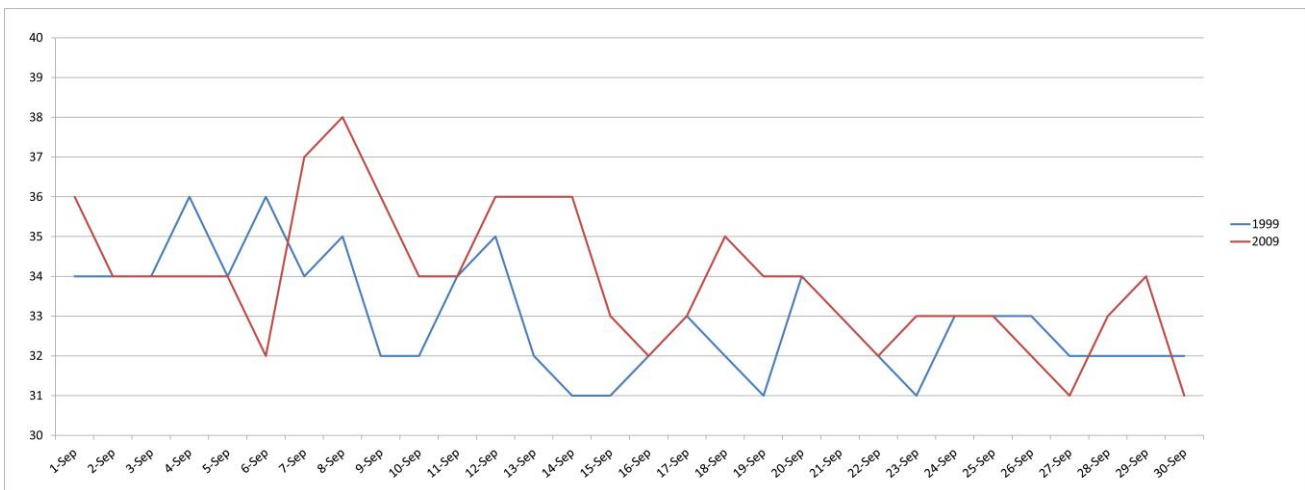


Figure 2 illustrates the visual results of the land cover classification as well as corresponding LST estimation. Note that there is an obvious increase in high-LST Bare Ground and High Intensity Urban areas in 2009. Figure 3 shows the ambient temperature recorded by the weather station in Dubai International Airport (Figure 1). There was a 1°C increase in the mean ambient temperature between 1999 and 2009, which could relate to the 2°C increase in mean urban LST. The intensified use of air conditioning during the summer months [23] should also be considered a factor that increases the ambient temperature. This increase is comparable with Saaroni and Ziv [24] who reported that UHI effect contributed an average of 0.64°C (10 yr)⁻¹ surge in summer temperatures in an arid city that experienced urbanization and increase in population (albeit at a slower pace than Dubai). According to Comrie [25] UHI effect caused an increase of 2°C in Tucson, Arizona over 30 years, which is within the decadal increase reported by Saaroni and Ziv. In comparison, Dubai's 1°C increase in temperature between 1999 and 2009 (Figure 3) is 35% higher than those studies because of the higher rates of population increase and urban expansion.

Figure 3. Average daily temperatures in degrees Celsius recorded by the Dubai International Airport weather station (OMDB) located at 25°15'35.91"N and 55°22'18.36"E (see Fig 1). Mean monthly air temperature for September 2009 was 1°C higher than September 1999.



The results presented here are consistent with previous studies [12, 13, 22, 24] that different types of land cover significantly influence LST and that increase in urban vegetation cover greatly reduces LST and by extension UHI. In this regard, LST can provide important acumens for urban design and management, wherein the local climatological influence of UHI can be controlled by balancing the comparative quantities of different land cover features (particularly vegetation) and improving their spatial arrangements.

4. Conclusions

In this letter, I conducted a preliminary characterization of the extent of land cover and surface temperature change in Dubai between 1999 and 2009 using Landsat ETM+ imagery. The accuracy of the land cover classification was 91.86% and 84.04% for the 1999 and 2009 land cover maps,

respectively. The applied methodology was successful in analyzing the spatial dynamics of land cover change and associated changes in daytime urban heat island effect. The study has implications for urban design and spatial planning in other rapidly expanding arid cities in the region.

The results suggest that the composition of land cover features significantly influence the magnitude of land surface temperature, and that the percent cover of stabilized land and impervious surfaces have the most substantial affect. In contrast, the percent of vegetation is the most essential driver of alleviating land surface temperature. Keeping the cooling effects of urban greenery in perspective, their proper management can directly mitigate the urban heat island effect in Dubai.

Change detection techniques in remote sensing are a viable tool in monitoring rapidly growing cities such as Dubai, and the 2008 Landsat open data policy from the United States Geological Survey [26] begun a new age for using time-series imagery for that purpose. The free availability of three decades of Landsat data provides invaluable insight into the dynamics of urbanization and its impacts on natural resources. On a broader scale, the world's urban population is projected to reach 9.3 billion by 2050 [27], making local climatic effects caused by urban environments a significant contributor to global climate change.

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Figure 4-S. The 2009 land cover map was validated using reference points collected from Google Earth imagery dated September 2, 2009.

Figure 5-S. A segment of the study area before (A) and after (B) implementing the fill procedure. The SLC-off gaps were not wide enough to introduce significant error into the interpolation.

